definitely; they will be past before we have had time—two, three, or four years—for the deliberate development of our plans. It is therefore with no idea of immediate action that the dreams of certain spare hours and days in the last two years have here been written down in brief outline; nor is it with the least intention or expectation on my part of sharing in the work of exploration, if the dreams are realized, that the outline is here presented. The work must be done by men of middle age or less, and they must be selected and directed by whomsoever brings the dreams into execution. If some antipodal Croesus rise to the occasion, the plan is his and welcome; but I believe that, if the plan is carried out at all, it will be by Americans, to whom the scientific conquest of the Pacific may make strong appeal. Even after the war is over, European munificence, if any of it survive, will be heavily burdened with home duties: and while the war lasts, even American capital may be so largely invested in commercial enterprises that little of it will be diverted to science: but when peace comes it is by no means beyond the limit of possibilities that our plan may arouse the interest of an American patron; for America's outlook upon the Pacific is large. Hence, in scientific as well as in national affairs, preparedness may well be our motto; and the first step in preparedness is—not a precipitate plunge into uncorrelated action—but the careful consideration of a comprehensive plan.

All that can be accomplished today is, to summarize a few of the broad problems that have been opened but not closed in the greatest of the world's oceans; and this will be done by the following speakers, who have generously responded to my appeal. Each one will touch briefly on certain topics—merely a few of many—yet representative, each one of all. I shall at some later time ask again if the whole subject, of which a few parts now are to be set before us, is not worthy of further consideration by the Academy, in the hope—not a vain hope, I believe—that the preparation of a well developed plan of investigation may be the prelude to a grand undertaking and a superb accomplishment.

THE IMPORTANCE OF GRAVITY OBSERVATIONS AT SEA ON THE PACIFIC

By John F. Hayford

COLLEGE OF ENGINEERING, NORTHWESTERN UNIVERSITY

Read before the Academy, April 17, 1916. Received, May 24, 1916

The time is ripe for decided advances in our knowledge of geodesy and geology to be made by a study of observed values of gravity. Observations for this purpose are needed at sea, especially—rather than

on land. On the seas a given amount of observing will produce most progress if that observing is done on the Pacific.

In geodesy, gravity determinations furnish the most powerful, the most accurate, known method of measuring the flattening of the earth, and thereby furnish the most severe, and therefore the most valuable, single test of the reliability of conclusions drawn from the deflections of the vertical which are put in evidence by triangulation and astronomic observations.

So also when conclusions have been reached as to the completeness and location of isostatic compensation on the basis of observed deflections of the vertical the most valuable single test of those conclusions is furnished by observed values of gravity.

The geodetic evidence as to the completeness and location of isostatic compensation furnishes effective tests of the validity of an important group of the fundamental ideas of geology. These tests are being applied by the geologists more frequently and more energetically each year.

Moreover, it has recently been shown by Mr. William Bowie,[1] that after observed values of gravity have been corrected for isostatic compensation the remaining anomalies, indicating outstanding excesses or deficiencies of density beneath the surface of the earth are, in some cases at least, related to the geological history of the region. It is probable that in due time geodesy will, in this line, furnish additional help to geology.

In general geodesy furnishes the most powerful known means of investigating the distribution of density beneath the earth's surface, to a moderate depth, say 200 miles. Hence any geological premise which depends on assumptions as to the distribution of densities, within that 200 mile zone—and there are many such premises—finds a severe test in the geodetic evidence. So geodesy may, and will, help the progress of geology.

Suppose it is granted that it is important to secure additional gravity observations. Why is it especially important to secure the additional observations at sea rather than on land?

Good determinations of gravity have already been made at 3000 widely scattered stations on the one-quarter of the earth's surface which is land. No reliable observations of the necessary degree of accuracy have been made on the three-fourths of the earth's surface which is covered by water.

As soon as it becomes possible to determine gravity satisfactorily on a moving ship at sea, it will be possible to secure observations so

rapidly at very widely scattered stations that the new observations made within a single year may furnish a more accurate value of the flattening of the earth than has yet been obtained from all the work of the past. Let us make this more definite and concrete. Assume that it becomes possible to take a series of observations on a moving ship which will determine the force of gravitation at the point of observation with a probable error of ± 0.008 dyne (about 4 times the probable error of a land determination). Past experience indicates that the probable error in one such result due to all causes, including the anomalous part of the distribution of densities beneath the surface, will be less than ± 0.020 dyne. Six hundred such observations could be secured in a single year scattered from latitude 60°N. to latitude 60°S. From these observations alone the value of the polar flattening of the earth could be computed more accurately than it has yet been computed.

Of course if the best observations that can be made at sea are of less accuracy than *this* their value will be less.

I am making this statement on the assumption that all such observations would be corrected for topography and isostatic compensation by the method now in use in the Coast and Geodetic Survey. Such corrections are essential to reliability and serve to increase greatly the accuracy of the computation of the flattening. I have just compared a very recent computation[2] by F. R. Helmert of the flattening of the earth with an older computation[3] of the flattening by William Bowie. Both used gravity determinations. Helmert used 700 widely scattered selected observations from among the 3000 available over the whole world. Bowie used 122 out of the 124 gravity observations in the United States alone. Helmert made no corrections for topography and isostatic compensation. Bowie applied such corrections. I am convinced from a study of the evidence, including the evidence of systematic errors, that Bowie's value of the flattening derived from 122 gravity observations in a small region is more accurate and reliable than Helmert's value from 700 carefully selected and widely scattered observations.

Observed values of gravity in the United States after correction for topography and isostatic compensation show no relation to the topography. On the other hand without such corrections, as Helmert's recent investigation again shows clearly, observations along the coasts stand in a class by themselves, observations in low interior regions in another class, those in mountainous regions in another class, and those on small oceanic islands in still another class, and each class is subject to its own peculiar systematic errors which are large.

It should be evident that it is extremely desirable to extend to the open oceans the proof, which is now conclusive for land areas, that the application of corrections for topography and compensation makes the corrected results independent of topographic effects and eliminates a large part of the systematic error otherwise inherent in the results. I am confident that good observations at sea will promptly furnish such a proof. They would certainly give a very severe and therefore very valuable test of the conclusions as to isostasy which have been drawn from the observations on land.

It is obviously important to determine as well as may be the prevailing depth at which masses of abnormal density lie. Are they ordinarily within 10 miles of the surface, or are they as frequently more than 40 miles down? The nearer to the surface such an abnormal mass lies the more rapid will be the space-change of gravity as an observer approaches, passes over, and recedes from the region on the surface which lies above the abnormal mass. For this purpose, therefore, for indicating the approximate depth of abnormal masses, it should be evident that closely spaced continuous lines of gravity observations at sea such as could be easily secured would be much more effective than are stations on land under ordinary conditions.

To what is the permanency, or semi-permanency, of the great oceanic depressions due? Adequate gravity observations at sea would establish conclusively the extent to which the rocks underlying the oceans are more dense than those under the land, and thus furnish a conclusive partial answer to the question.

The present indications, from a few gravity stations on such islands, is that gravity is in excess on oceanic islands, such as the Hawaiian Islands, where vulcanism is active. How far does said excess extend out to sea? Observations of gravity at sea would answer that question and in doing so might contribute much to our knowledge of the nature and cause of vulcanism.

What is the nature of the deep troughs that occur at various places in the oceans and which show a suggestive tendency to be located near and parallel to an elongated land area or a mountain chain? Gravity observations at sea may throw a light upon this question by showing the density of the rocks below such troughs.

I have indicated why I believe it to be especially important to secure gravity observations at sea. If such observations are to be made, why is the Pacific the ocean upon which they will be most effective?

Of course it occurs to one at once that the Pacific is the greatest ocean and that therefore the largest blanks in which there are now no gravity

observations are there. That will on examination prove to be a more weighty consideration in favor of the Pacific than appears at the first glance.

Two other considerations also combine with this to indicate strongly that the Pacific is the most effective place to make gravity observations at sea in order to advance our knowledge of geodesy and geology.

First, it is important to get observations at sea so far from any continent as to be certainly free from any continental effect.

It is difficult to get 2000 miles from all continents on the Atlantic. That distance is not sufficient. On the Pacific there is a considerable area 3000 miles from any continent. The Pacific ocean occupies the water hemisphere.

The second consideration in favor of the Pacific is that it offers an unequaled variety of special opportunities to study special questions under extreme and contrasting conditions. In it there are small oceanic islands of volcanic origin far from land, and equally small oceanic islands far from land apparently not of volcanic origin. There are several troughs more than 8000 meters deep lying adjacent to large islands in some cases and in others far from any but very small islands. There are flat bottomed areas of more than 6000 meters depth of various sizes, some covering several square degrees, and in various relations to land. There are several areas of less than 200 meters depth, some of which are far from any land, except very small islands. No other ocean offers an equal variety of equally favorable opportunities for special studies based on gravity observations at sea.

Adequate observations of gravity, at sea, on the Pacific Ocean would contribute greatly to progress in geodesy and geology.

[1] Special Publication No. 10 of the Coast and Goedetic Survey, pp. 113–117 and Special Publication No. 12, pp. 18–21. Both these publications are under the title Effect of Topography and Isostatic Compensation upon the Intensity of Gravity.

[2] "Neue Formeln für den Verlauf der Schwerkraft im Meeresniveau beim Festlande," von F. R. Helmert; Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften, 1915, XLI, Gesamtsitsung vom 21 Oktober.

[3] Special Publication No. 12 of the Coast and Geodetic Survey, pp. 24–26.